IMPORTANCE OF PROCESSES OF NATURAL VENTILATION TO FUMIGATION AND CONTROLLED ATMOSPHERE STORAGE

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Abstract: For either fumigation or controlled atmosphere (CA) treatments, gas losses from the treatment enclosures caused by the processes of natural ventilation must be reduced to a very low rate. A model is presented which may be used to calculate the total rate from the maximum expected individual contributions of the various phenomena giving rise to gas loss. The ventilation rates expected from wind and the chimney effect are dependent on the level of sealing of the enclosure and are given in terms of the decay time, as assessed by a pressure decay test. The ventilation produced by temperature and barometric variation is not very sensitive to the level of sealing. The magnitude of the ventilation expected from the leak-dependent and -independent effects are compared for four types of storage. The relevance of this method of analysis to fumigation and CA treatments is discussed and maximum rates of loss tolerable by various methods are given. It is concluded, *inter alia*, that

(a) the pressure decay test time is only an approximate indication of the possible gas loss rate,
(b) the decay time specified for a particular system should take into account the influence of the expected environmental forces and geometry of the enclosure,
(c) it may be necessary to curtail gas loss by methods other than sealing after a certain minimum standard is reached, and
(d) it is unlikely that the gas loss rate in storage structures can be reduced to a level permitting simple hermetic storage of dry grain without very efficient thermal insulation and sealing.

INTRODUCTION

Both fumigation and controlled atmosphere techniques for insect control in grain rely on alteration of the composition of the gas mixture within an enclosure. The enclosure may be either a permanent structure, such as a grain storage, or a temporary system, such as a fumigation tent or a grain bulk covered with a PVC membrane. The gases added to alter the atmosphere in the enclosure may be either toxic ones, such as in fumigations with methyl bromide or phosphine, or particular atmospheric constituents, such as CO_2 or nitrogen, as used in controlled atmosphere (CA) techniques. After modification of the enclosed atmosphere, the average and local compositions of the gas mixture must be maintained within predetermined limits for the exposure period. If the treatment is to be carried out efficiently and safely with minimal use of added material only a very low rate of natural ventilation is permissible. Table 1 gives the maximum ventilation rates tolerable for various treatments. In simple grain storage enclosures such low rates can only be attained if specific and often costly measures such as sealing are taken to minimise gas losses.

TABLE 1.

Ventilation rates tolerable in various insect control processes using gases.

Process	Maximum ventilation rate (d^{-1})	Reference
Hermetic storage of dry grain	0.026	based on Oxley *et al.*, 1960
N_2-based CA (long term exposure)	0.05	Banks and Annis, 1977
CO_2-based CA ('one-shot')	0.07	Banks *et al.*, 1980
Phosphine fumigation	0.10	Unpublished estimate (Banks and Annis)

For the optimal application of measures designed to reduce gas loss it is important to understand in quantitative terms the natural processes that cause gas loss from a structure. For instance, an appreciation of the underlying phenomena may provide a means to assess whether, in a practical situation, further attempts at sealing are of any practical value. Hitherto, studies of natural ventilation of buildings and other enclosures for grain storage have been concerned either with very well sealed or with intentionally ventilated systems. In the first case, gas loss can be described as a function of the variation in ambient and internal temperature and pressure (Barker, 1974; Newman, 1970; Moller and Pedersen, 1978; Meiering, 1982). In the latter case (see Banks *et al.*, in press), as with habitable structures (Macriss *et al.*, 1979; Anon., 1972; Blomsterberg and Harrje, 1979; Peterson, 1979), the ventilation rate is determined largely by the wind and the chimney effect for a certain level of sealing. In practice the gastightness of most enclosures to be treated with fumigants and controlled atmospheres is intermediate between these two extremes and all these forces can have a significant effect on gas loss.

This paper provides a simplified mathematical description of the action of the various forces involved in the natural ventilation of enclosures. The description can be used to predict the variation in the contribution of the various forces to the total gas loss under different environmental conditions and gastightness of the enclosure. It will be shown that a pressure decay test standard for the assessment of gastightness is not a precise concept and that there is a degree of judgement which must be applied in the setting of standards for particular situations. Furthermore, there are some forces whose contribution to total gas loss can be significant but which can best be restricted by strategies other than sealing.

In general the model is similar to that used by Banks *et al.*, (1975) to describe gas loss from freight containers, but with changes and some minor additions so that it is specifically applicable to grain storage systems and incorporates a term to describe particular flow characteristics of leaks.

Previously, there has been no conceptual framework available which would predict the dominant cause of failure in fumigants or CA treatments. A number of different single forces have been implicated in such failures in the past (e.g. wind (see Mulhearn *et al.*, 1976), chimney effect (Oxley and Howe, 1944; Bond *et al.*, 1977), diffusion (Lewallen and Brown, 1967)). An understanding of the contribution of the various forces causing gas loss, as provided below, may help to determine some of the environmental causes of failures in particular circumstances with more confidence than hitherto, and perhaps show how these problems can be avoided.

2. THEORETICAL BASIS OF MODEL†

The gas loss from an imperfectly sealed enclosure is largely dependent on the pressure across the leaks in the enclosure fabric and the size and flow characteristics of these leaks. There is an additional, small component of loss associated with molecular diffusion and therefore dependent on the gas composition of the enclosed and external systems. A number of simplifying assumptions are made here in order to describe the gas loss rate from an en-

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† The notation used is summarized below.

closure with a conservative and easily evaluated model, suitable for design studies. These are:

(a) *The gaseous contents of the enclosure are well mixed, so that any element of volume lost will be at the average concentration of the contained gases at that moment.* In practice some of the gas lost may be regained in a cyclic process. Similarly air entering may be subsequently expelled without mixing. Also occasionally gas may be lost from a region rich in a particular component. The first two processes result in a lower effective ventilation rate than expected (as discussed by Malinowski (1971)) while the latter increases the rate.

(b) *That each of the forces causing gas loss acts independently and that their effects may be summed to give an estimate of the total gas loss.* It can be shown that the total interchange is never greater than the sum of the expected effect of each force acting in isolation (Sinden, 1978).

(c) *That the empirical equation*

$$Q = b\Delta p^n \tag{1}$$

describing the flow of gas, Q, through a leak with pressure difference, Δp, (Anon. 1972; de Gids, 1977; Blomsterberg and Harrje, 1979) holds throughout the range of pressures created by the individual forces without change of either the coefficient, b, *or the exponent,* n. When it is necessary to show the direction of the leakage, Equation (1) is used in the form

$$Q = b\frac{\Delta p}{|\Delta p|^{1-n}} \tag{2}$$

so that, Q, is positive when gas is lost from the enclosure and $\Delta p > 0$ (i.e. internal pressure > external pressure). Equation (1) is known not to hold over a wide pressure range and to be dimensionally unsound (Kreith and Eisenstadt, 1957), but to be a reasonable approximation (de Gids, 1977) over the pressures, 1 to 100 Pa, likely to cause significant ventilation in grain.

(d) *That the total leak area over a storage can be represented by two composite leaks with similar flow characteristics (i.e. same value of* n*) and of equal area and that the two leaks are distributed such as to maximise the effect of each individual force.* This may require that the leaks have different positions simultaneously for different forces.

(e) *That the variation in particular forces (e.g. temperature variation, wind pulsation) can be represented as sinusoidal functions of time.*

The overall effect of these assumptions is to provide a model which gives the maximum effect expected from each individual force and the maximum total ventilation rate for a particular set of conditions. In practice because of interactions between the individual forces and also the distribution of leaks the actual loss rate will usually be substantially less than predicted by the model. Allowance for this will be made in subsequent discussion.

To provide a complete description of gas loss over time, it is necessary first to consider three interrelated problems: (a) the description of gas losses produced by pressure or concentration differences across leaks, (Section 2.1) (b) the description of pressure or concentration gradients as produced by various environmental forces (Section 2.2) and (c) the description of the sealing level of an enclosure in a form which can be used to assess the effect on gas loss of pressure or concentration gradients across the enclosure walls (Section 2.3)

2.1 GAS TRANSFER EQUATIONS

2.1.1 Flow Through Leaks

Bulk flow of gas occurs through a leak where there is a pressure differential Δp, across that leak as described by Equations (1) or (2). The value of n varies between 0.5 and 1.0, depending on the flow characteristics of the leaks. In cases where $n = 0.5$, the value of b can be related to the area of the leak present through Torricelli's law (Kreith and Eisenstadt, 1957). Thus

$$b = \gamma A \sqrt{\frac{2}{\rho}} \qquad (3)$$

When $n \neq 0.5$, a true size of leak cannot be given without detailed knowledge of the geometry of the leaks.

Some forces cause losses from all leaks simultaneously (e.g. thermal expansion), while others (e.g. wind) give a flow of gases through the enclosure, air entering at one point and the enclosure gases being lost at another. In the first case, Equation (1) applies. In the second, for the purposes of this model, the total leak of effective size, b, is divided into two leaks with equal value of n. It can be shown that the flow through two such leaks in series is given by

$$Q = b\Delta p^n \left(\frac{1}{\alpha^{-1/n} + (1-\alpha)^{-1/n}} \right)^n \qquad (4)$$

where α is the proportion of the total leak area represented by the smaller leak, and for α = 0.5 (i.e. two equal leaks in series)

$$Q = \frac{b\Delta p^n}{2^{n+1}} \qquad (5)$$

The magnitude of most of the forces involved in gas leakage varies with time. This gives rise to fluctuating pressures across the leaks with frequencies varying from many cycles per second, as in some components of wind turbulence, to yearly cycles, as with seasonal heating and cooling. Substituting in Equation (2), the flow at any instant then is given by

$$Q = b\frac{\mathrm{f}(t) - \mathrm{f}'(t)}{|\mathrm{f}(t) - \mathrm{f}'(t)|^{1-n}} \qquad (6)$$

where f(t) and f′(t) are time-dependent functions describing the internal and external pressures.

2.1.2 Evaluation of Ventilation Rates

The ventilation rate[†], k, is defined as (e.g. Lagus, 1977):

$$k = \frac{\Delta V}{Vt} = \frac{Q}{V} \qquad (7)$$

and, at constant density,

$$k = \frac{\Delta m}{mt} \qquad (8)$$

The ventilation rate is used here as a measure of the effect of the various forces, where V and m are the volume and mass of gas within the enclosure, Q is the volumetric rate of loss of gas and ΔV is the volume of gas lost at constant pressure and Δm the mass of gas lost over time, t. Note that the ventilation rate is calculated on the basis of flow in one sense only, in or out of the enclosure.

The ventilation rate is a measure of rate of loss of a gaseous component from a system since

$$c_2 - c_{ext} = (c_1 - c_{ext})\mathrm{e}^{-kt} \qquad (9)$$

where c_1 and c_2 are the initial concentrations of the component and the concentration after time, t, within the system and c_{ext} is the

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[†] Also known as the air change rate, the infiltration rate, gas interchange rate or gas loss rate constant and sometimes, incorrectly, simply as the gas loss rate.

external concentration of the component.

For evaluation of k, it is often convenient to express the losses in terms of rate of mass loss from the system. Since

$$Q = -\frac{1}{\rho}\frac{\mathrm{d}m}{\mathrm{d}t} \tag{10}$$

the rate of loss of mass is given by

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \rho b \frac{\mathrm{f}(t) - \mathrm{f}'(t)}{|\mathrm{f}(t) - \mathrm{f}'(t)|^{1-n}} \tag{11}$$

combining Equations (6) and (10). Generally, for the periodic functions encountered here, this expression is best solved iteratively with the change in mass estimated over one or more complete cycles. The change in mass, δm, during the i^{th} interval of δt is given by

$$\delta m = \rho b \left(\frac{\mathrm{f}(t_i) - \mathrm{f}'(t_i)}{|\mathrm{f}(t_i) - \mathrm{f}'(t_i)|^{1-n}} - \frac{\mathrm{f}(t_{i-1}) - \mathrm{f}'(t_{i-1})}{|\mathrm{f}(t_{i-1}) - \mathrm{f}'(t_{i-1})|^{1-n}} \right) \tag{12}$$

and

$$\Delta m = \frac{\sum|\delta m|}{2} \tag{13}$$

The average interchange rate can then be found using equation (8).

The actual interchange produced by a fluctuating pressure difference is dependent on the response time of the contained system, here measured as the pressure decay time, t_d (see Section 2.3), relative to the period of fluctuation, τ. When t_d is small compared with τ, the interchange can be calculated directly from the amplitude of the fluctuations (i.e. with no damping of effect). When t_d is similar to or greater than τ the actual interchange is less than this value and dependent on the ratio of t_d to τ and the value of n as shown in Figure 1. The values in Figure 1 were calculated by evaluating the equation

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\rho b \frac{\frac{mR\overline{T}}{VM}(1 + a\cos\omega t) - p_{ext}}{|\frac{mR\overline{T}}{VM}(1 + a\cos\omega t) - \overline{p}_{ext}|^{1-n}} \tag{14}$$

iteratively until a stable value of the interchange per cycle was obtained, with b, a function of t_d, given by Equations (33) or (34). This rate was then expressed in terms of time units of t_d/τ Equation (14) is derived from Equation (11) with f(t), the internal pressure, given by

$$f(t) = \frac{mRT}{VM} \tag{15}$$

and $f'(t)$ the external pressure,

$$f'(t) = \overline{P}_{ext}(1 + a\cos\omega t) \tag{16}$$

It can be seen that when $\tau > 10t_d$ there is little damping in effect but when $\tau < 10t_d$ the interchange produced by a fluctuating pressure will be reduced compared with the expected undamped value.

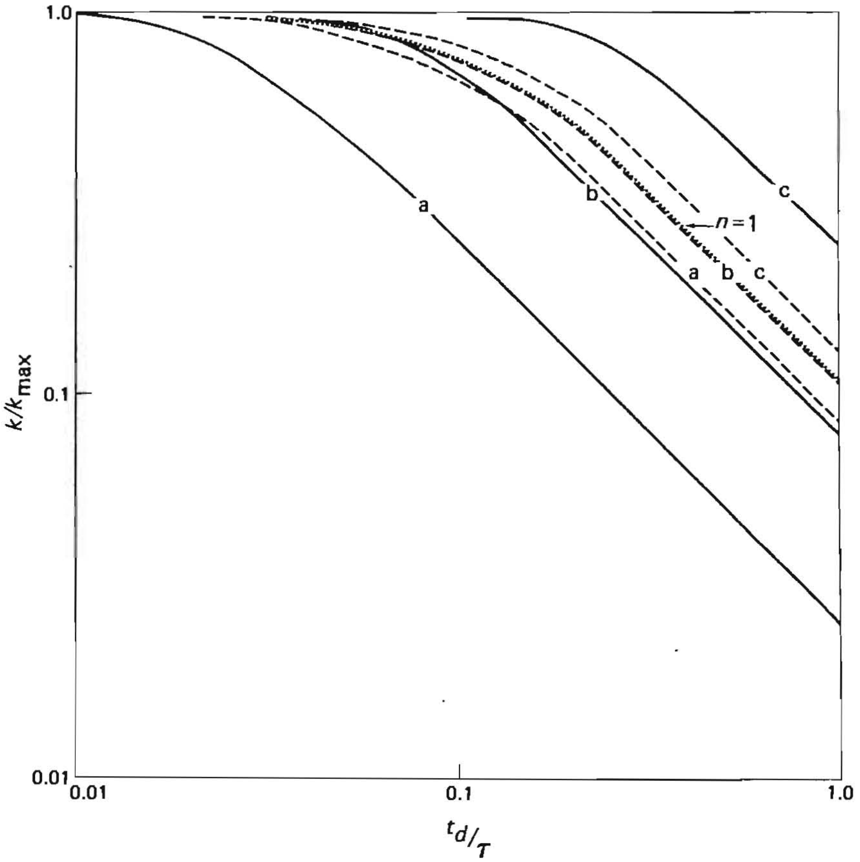

Fig. 1. Damping effects for cyclic phenomena with periods of similar magnitude to the decay time (500-250 Pa), t_d, for amplitude values of $a = 10^{-1}$, 10^{-2} and 10^{-3} (lines marked a, b and c respectively) and values of $n = 0.5$ (——), 0.8 (-----) and 1.0 (┄┄┄) (One line only for $n = 1.0$ as this is independent of value of a). Calculated from Equation (15) as described in text.

2.2 EFFECTS OF INDIVIDUAL FORCES

Gas losses through leaks from an enclosure containing stored grain can be caused by the following phenomena:

a. Temperature variation;
  a.1 Variation in the headspace,
  a.2 Variation in the bulk.
b. Barometric pressure variation;
  b.1 Tidal variation,
  b.2 Long term (synoptic) variation.
c. Wind;
  c.1 Wind at a steady speed,
  c.2 Fluctuating components of wind (pulsation and turbulance).
d. The chimney or stack effect;
  d.1 Driven by temperature variation externally,
  d.2 Driven by composition differences.
e. Molecular diffusion.
  e.1 Diffusion through leaks,
  e.2 Permeation.

2.2.1 Temperature variation

There are two thermally distinct regimes in an enclosure around a grain bulk: the headspace and the grain bulk. These must be treated independently to calculate the gas loss from a storage, since while the temperature in the headspace may change rapidly in response to changing ambient conditions, the temperature of most of the bulk changes only very slowly because of its low thermal diffusivity.

2.2.1.1 Temperature variation in the headspace.

The temperature in the headspace fluctuates with the daily cycle of temperature and solar radiation. Superimposed on this daily change there may be shorter period fluctuations caused by changes in solar radiation, wind cooling and ambient temperature. Because the period of the daily cycle is long compared with the pressure decay time of sealed storages (see Section 2.1), pressure equilibrium is maintained across the storage fabric during the heating and cooling cycle. It can be shown, from simple gas laws, that the quantity of gas lost, ΔV, during a cycle of amplitude ΔT is then given by

$$\Delta V = \frac{V_{HS}\,\Delta T}{T_{min}} \qquad (17)$$

and thus the ventilation rate due to temperature variation, k_T, is given by

$$k_T \doteq \frac{V_{HS}}{V}\frac{\Delta T}{T_{min}t}, \ \Delta T \geqslant 0 \tag{18}$$

When the time period of the variation in headspace temperature is similar to or less than the pressure decay time of the enclosure, there will be a periodic pressure difference across the leak and the actual interchange will be less than expected from Equation (18). The quantity of gas lost can be calculated using Equation (7) with Δm estimated numerically as previously (Equations (12) and (13)) from the equation:

$$\frac{dm}{dt} = -\rho b \frac{\frac{mRT}{VM} - \bar{p}_{ext}(1 + a\cos\omega t)}{\left|\frac{mRT}{VM} - \bar{p}_{ext}(1 + a\cos\omega t)\right|^{1-n}} \tag{19}$$

an equation derived from Equation (11) with

$$T = \bar{T}(1 + a\cos\omega t) \tag{20}$$

2.2.1.2 Temperature variation in the bulk

External temperature fluctuations cause grain in contact with exposed parts of the enclosure to change in temperature, leading to changes in temperature of the interstitial gases with consequent pressure changes and possible leakage. Daily temperature fluctuations, unlike long term seasonal fluctuations, do not penetrate far into the grain bulk (ca. 10 cm, (Babbitt, 1945)).

It can be shown (see Appendix) that a grain bulk subject to a periodic external temperature variation obeying Equation (20) at its surface, loses gas at a rate, k_{Tb}, given by

$$k_{Tb} = \frac{2aNA}{\bar{T}Vt}\sqrt{\frac{\kappa}{\omega}} \tag{21}$$

2.2.2 Barometric pressure variation

Atmospheric pressure undergoes tidal and long-term cyclical fluctuations with some abrupt changes caused by atmospheric phenomena such as thunderstorms and cyclones. A change in external pressure will result in a pressure difference across leaks, ΔP, in an enclosure resulting in losses given by

$$\Delta V = \frac{V\Delta P}{P_{max}} \tag{22}$$

Thus the ventilation rate, k_p, caused by these changes is given by

$$k_P = \frac{\Delta P}{P_{max}t}, \Delta P \leqslant 0 \tag{23}$$

Because barometric fluctuations have long periods compared with storage pressure decay times, there is no appreciable damping of effect from sealing (see Section 2.1).

Note that barometric fluctuations cause loss from the complete gas volume in the enclosure (i.e. both headspace and interstitial spaces) in contrast to some types of temperature variation.

2.2.3 Wind.

The effect of wind can be divided into two components: that produced by the mean steady wind speed and that produced by fluctuations from pulsations and turbulence about this mean speed.

2.2.3.1 Mean wind speed effect

The pressure induced by wind at a point is given by (Mulhearn *et al.*, 1976; de Gids, 1977)

$$\Delta p = \frac{C\rho u^2}{2} \tag{24}$$

where C is a pressure coefficient varying with the location of the measuring point and orientation relative to the wind. The interchange rate is then given by

$$k_w = \frac{b}{2^{n+1}V}\left(\frac{\Delta C\rho u^2}{2}\right)^n \tag{25}$$

where ΔC is the difference in the pressure coefficients at the two leaks (substituting in Equation (5) and then (7)). The actual value of the interchange produced will be sensitive to ΔC. Many parts of a storage will have C values close to zero, but some small regions may have values exceeding ± 2.0 (Mulhearn, *et al.*, 1976; Banks *et al.*, in press). ΔC can thus vary from approximately zero up to 4.0 in exceptional cases.

2.2.3.2 Wind pulsation and turbulence

The loss rate to be expected from wind pulsation and turbulence cannot be estimated accurately for grain storage enclosures as it is subject to too many random factors and computational uncertainties.

The mechanisms by which pulsation and turbulence can cause gas loss have been discussed by Malinowski (1971). He recognised that because of the rapid change in direction of flow of gas through a leak driven by these forces, the actual interchange produced may be a small fraction of that of the theoretical maximum. Air entering at one time may be largely expelled at another, bringing with it little of the internal gases (Cockroft and Robertson (1976) found only about one third of the air entering under their conditions mixed with the internal gases). The actual fraction will be dependent on the frequency and amplitude of pulsation and the rate of mixing within the system and has not been studied adequately for reliable values to be available. Because there is a broad range of frequencies of fluctuation involved, the approximations used to calculate the damping of the effect of single frequencies, as for Fig. 1, may not be appropriate. Furthermore, in most practical situations, pressures from wind fluctuations will be superimposed on substantial mean wind pressures. In such cases and where there is already leakage caused by these pressures, the fluctuations will merely modulate the flow and cause little change in interchange rate, except on those occasions where the amplitude is sufficient to change the sign of Δp and thus reverse the flow of gas through the leak.

In view of these uncertainties, we do not attempt to treat the wind pulsation and fluctuation effects mathematically but, based on data in Hill and Kusuda (1975), we assume

$$k_{wf} = 0.2 k_w \tag{26}$$

2.2.4 The chimney effect

The density of the gaseous contents of an enclosure may differ from that externally, either because it is of a different composition or at a different temperature. These density differences result in pressure differences across the enclosure fabric, causing gas loss if leaks are present. This phenomenon is known as the chimney or stack effect. The pressure difference across two leaks separated by a vertical distance, h, is given by (de Gids, 1977)

$$\Delta p = (\rho_{int} - \rho_{ext}) g h \tag{27}$$

With the external density, ρ_{ext}, varying with daily temperature fluctuations thus,

$$\rho_{ext} = \frac{MP}{R\overline{T}(1 + a\cos\omega t)} \tag{28}$$

and with the period of fluctuation much greater than the pressure decay time and the internal density remaining approximately constant, the rate of gas loss from this effect, at time, t, is given by

$$Q = \frac{b}{2^{n+1}}\left[gh\left(\frac{MP}{R\,\overline{T}(1 + a\cos\omega t)} - \rho_{int}\right)\right]^{n} \tag{29}$$

and the average value of the ventilation rate from the chimney effect, k_c, over the cycle

$$k_c = \frac{1}{2V}\int_0^{2\pi}\frac{b}{2^{n+1}}\left[gh\left(\frac{MP}{R\,\overline{T}(1 + a\cos\omega t)} - \rho_{int}\right)\right]^{n} d(\omega t) \tag{30}$$

2.2.5 Diffusion and Permeation

Losses by true molecular diffusion through leaks are always small compared with those created by other forces. The ventilation rate from diffusion, k_D, through a leak of area, A, and length, l, is given by (from Lewallen and Brown, 1967)

$$k_D = \frac{DA}{Vl} \tag{31}$$

Losses by permeation through the fabric of an enclosure are described similarly:

$$k_{pe} = \frac{KA'}{Vl'} \tag{32}$$

where l', is the thickness of the film and A', the area over which permeation occurs.

It will be noted that permeation refers to true transfer through the mass of the fabric of a permeable but intact film, such as PVC sheet, but is to be distinguished from gas losses through small imperfections, such as porosity in concrete, where bulk movement of gas occurs.

2.3 RELATING PRESSURE TEST DATA TO LOSS RATES

In the model given here, the pressure decay time, t_d, of the enclosure, as measured by a pressure decay test, is used as a measure of gastightness. In this test, air is introduced into the structure to raise the internal gas pressure to a value Δp_1 above atmospheric. The air supply is then shut off and the pressure is allowed to fall by natural leakage to a new value Δp_2. The time taken to fall from Δp_1 to Δp_2 is then a measure of the degree of sealing. Assuming isothermal conditions the time for the decay, t_d is given by (Sharp, 1982)

$$t_d = \frac{(\Delta p_1{}^{1-n} - \Delta p_2{}^{1-n})\,VM}{(1-n)RT\rho b}\,,\ n \neq 1 \tag{33}$$

and

$$t_d = \frac{(\ln\Delta p_1 - \ln\Delta p_2)\,VM}{RT\rho b}\,,\ n = 1 \tag{34}$$

These equations relate t_d to b for a particular value of n. Since these parameters also occur in expressions for k_w and k_c it is possible to relate k_w and k_c directly to a set decay time by substituting for b as found from Equations (25) or (30).

Pressure decay testing in its simple form does not determine the value of n. The value of n lies between 0.5 and 1.0 and, generally, for well sealed storage structures $0.8 < n < 1.0$ (Banks and Annis, unpublished data). We will use $n = 0.8$ as a the minimum likely value for subsequent example calculations. (Note: Meiering (1982) gave estimates of gas loss rates from silos under various levels of sealing but did not include wind and chimney effects and considered $n = 0.5$ only).

3. VALUES OF THE CONTRIBUTION OF INDIVIDUAL FORCES TO LOSS

Using the expressions given above, it is possible to calculate the maximum contribution of each individual force causing gas loss from an enclosure of defined standard gastightness, if the values of the various environmental parameters concerned are known. Table 2 gives the calculated gas interchange rates caused by the various forces for four enclosures, detailed in Table 3, sealed to give a 5 min decay time (t_d) from 500 to 250 Pa in a full structure. This time has been adopted by the Coordinating Committee on Silo Sealants in Australia as a design standard for fumigable structures. The parameter values used here to define the main forces are reasonable high values for grain storages in the open in summer in inland Australia, chosen from our own experience.

It can be seen from Table 2 that the effect of some forces is very dependent on the value of n, even though the enclosures give a fixed decay time. Furthermore, some forces cause negligible gas losses, < 0.005 day^{-1} (e.g. diffusion, synoptic variation of barometric pressure), but others have a major effect, notably wind and temperature variation. Furthermore, the ventilation produced by diffusion and by wind and the chimney effect is dependent on the

TABLE 2.

Interchange rates (day^{-1}) calculated for individual phenomena for a sealing level giving a 5 min pressure decay time (500 - 250 Pa).

Phenomenon	Parameter values used	Case 1 Farm bin			Case 2 Bag stack			Case 3 Silo bin			Case 4 Shed		
Temperature variation in headspace (daily)	Range: 10-40°C (Case 1, 2, 4) 20-35°C (Case 3)	.025			.012			.007			.045		
Short term temperature fluctuation in head space	± 2°C (Case 1, 2) ± 1°C (Case 4) ± 0.5°C (Case 3) every 30 mins for 12 hours	.034			.007			.009			.042		
Daily variation in grain bulk	Skin temperature variation 12-40°C (25.5 - 29.5, Case 3) $\kappa = 10^{-2} m^2 d^{-1}$, $N = 0.38$	.009			.002			<.001			<.001		
Barometric pressure variation (tidal)	± 1.5 mb about 1013 mb twice daily	.006			.006			.006			.006		
Barometric pressure variation (synoptic)	± 12 mb about 1013 mb every 6 days	.004			.004			.004			.004		
Permeation	Permeation coefficient .0025 g mm d^{-1} m^{-2} (g m^{-3})$^{-1}$, thickness 0.8 mm (Case 2 only)	-			.004			-			-		
								VALUE OF n					
		0.5	*0.8*	*1.0*	*0.5*	*0.8*	*1.0*	*0.5*	*0.8*	*1.0*	*0.5*	*0.8*	*1.0*
Steady wind	6.4 m s^{-1} (Case 1), 7.9 m s^{-1} (Case 2), 12.0 m s^{-1} (Case 3), 10.9 m s^{-1} (Case 4). $C = 2.0$	.090	.041	.024	.112	.057	.036	.169	.111	.083	.155	.095	.069
Wind pulsation and turbulence	Assumed 0.2 x steady wind value	.018	.008	.005	.022	.011	.007	.034	.022	.017	.031	.019	.014
Chimney effect driven by temperature variation	Internal temp. 27.5°C, daily external variation 15-40°C.	.010	.001	<.001	.014	.002	<.001	.037	.010	.004	.029	.007	.003
Chimney effect driven by composition differences	As above, but with 60% CO_2 internally	.035	.009	.004	.045	.016	.007	.135	.077	.053	.105	.051	.032
Diffusion	Diffusion coefficient $2 \times 10^{-5} m^2 s^{-1}$, path length 3mm, area of leak 1.6mm^2 (Case 1), 76mm^2 (Case 2), 650mm^2 (Case 3), 2000mm^2 (Case 4).	<.001	a	a	<.001	a	a	<.001	a	a	<.001	a	a

a Area of leak not calculated for $n \neq 0.5$. Rate constant likely to be <<0.001 d^{-1}.

TABLE 3.

Details of storage enclosures used as examples for calculation of interchange rates.

Case No.	Storage (construction material)	Nominal capacity (wheat, tonnes)	Gas volume (loaded, m^3)	Head space volume (m^3)	Exposed Surface area (m^2)	Dimensions
1	Farm bin (unpainted, galvanised iron)	5	3.0	0.6	15.9	Cylindrical wall 2.1 m diam., 1.8 m to eaves. 30° roof pitch.
2	Bag stack (PVC - covered)	100	140	5	190	Rectangular 11.5 x 4.7 m, 4.2 m high.
3	Silo bin (unpainted, concrete)	2200	1220	160	1090	Cylindrical wall 11 m diam., 30 m to eaves. 30° roof pitch.
4	Flat storage (unpainted, galvanised iron)	55000	41300	15200	14200	Rectangular plan 137 x 52 m, 5.2 m to eaves. 30° roof pitch.

size and type of leak in an enclosure (i.e. dependent on values of b and n) while the effect of others is independent of leak size, except at very high degrees of sealing, where there is some damping of effect.

The sum of the interchange rates resulting from individual forces in the two groups are referred to here as $(k_{dep})_{max}$ and $(k_{indep})_{max}$ respectively. Thus

$$(k_{dep})_{max} = k_w + k_{wf} + k_c + k_d \tag{35}$$

and

$$(k_{indep})_{max} = k_T + k_{Tb} + k_P + k_{pe} \tag{36}$$

These rates are calculated using high values of the controlling parameters and without allowance for interactions and chance effects. They thus represent maximum values and are unlikely to be attained in practice, except in exceptional combinations of circumstances. Generally:

$$k_{dep} + k_{indep} \ll (k_{dep})_{max} + (k_{indep})_{max} \tag{37}$$

The actual value of k_{indep} may be slightly less than the estimate, $(k_{indep})_{max}$, as there may be some interaction between temperature and barometric effects so as to reduce the total effect. However, even when k_p is acting in directly the opposite sense to k_t its influence on k_{indep} will be small since k_p itself is small. The actual value of k_{dep} is much less accurately known but may possibly be less than half that of $(k_{dep})_{max}$. To achieve maximal effect from wind and the chimney effect the effective leaks must be of equal size and located both in regions of high and low C values, effectively across the structure, and also at the top and base of the bin. These two conditions cannot hold simultaneously. Furthermore, if the two effective leaks in series, required for the wind and the chimney effect to produce gas interchange, are not of equivalent size the expected interchange will be reduced. This effect is summarised in Table 4 (see also Anon. 1972, p.344). Also there is an interaction between the wind and chimney effect such that their combined action is less than the sum of the expected individual contributions.

Despite these uncertainties, the calculated values of $(k_{dep})_{max}$ and $(k_{indep})_{max}$ provide useful semiquantitative information on the effects of sealing and whether other strategies may be necessary to reduce gas losses to within a tolerable range for a particular process.

Figures 2a-2d show the variation in $(k_{dep})_{max}$ with pressure decay time, t_d, for the four types of storage treated in Table 3. The values of $(k_{indep})_{max}$ are also shown. The values of the two interchange rates are summarised for t_d = 5 mins in Table 5.

The following deductions can be made from information in Fig. 2 and Table 2.

(1) Sealing to a level that gives at least a few minutes pressure decay test time reduces $(k_{dep})_{max}$ very substantially. (Note: in the model used here $(k_{dep})_{max}$ is inversely proportional to t_d.)

(2) That the value of n has an important influence on the value of $(k_{dep})_{max}$ with the greater interchange expected with lower values of n for the same decay time.

(3) That the relative importance of leak-dependent and -independent interchange rates varies with type of structure. With the silo bin, $(k_{dep})_{max}$ is large relative to that from the farm bin, suggesting a higher sealing standard should be applied in the former case to give the same rate of interchange.

(4) The value of $(k_{indep})_{max}$ in three cases considered is similar in magnitude to the rates tolerable for phosphine fumigation and CA processes (Table 1). Even allowing for the uncertainty in the actual value of this parameter, some reduction in its value appears necessary as there is otherwise little latitude in the specification for the additional effects of wind and the chimney effect. Since reduction of k_{indep} cannot be achieved by sealing, it must be done by some other strategy (e.g. reduction of temperature variation by white-painting or shading, and use of breather bag systems).

(5) It appears unlikely, in the structures assessed, here that the leak-dependent losses can be reduced by sealing to a level which would permit hermetic storage (Table 1) even allowing for the interactions and chance factors discussed above.

(6) The value of $(k_{dep})_{max}$ appears excessive in the case of the silo bin at the currently used standard pressure decay time (5 mins, 500 - 250 Pa in a full system) for fumigable bins. It may be that some increase in the decay time standard is warranted to ensure that gas loss is not excessive even under very adverse environmental conditions. However it may also be

TABLE 4.

Influence of leak distribution on calculated loss rate for Case 3 (t_d = 5 mins, 500 - 250 Pa, full structure) for wind and chimney effect.

Ratio of leak area for air entry to gas loss	Value of α in Equation (4)	Calculated ventilation rate (day^{-1})^a	
		Wind	Chimney effect with 60% CO_2 internally
1 : 1	0.50	0.084	0.053
1 : 2	0.33	0.074	0.047
1 : 3	0.25	0.063	0.040
1 : 5	0.167	0.046	0.029
1 : 10	0.091	0.028	0.018

[a] Calculated using Equations (4), (7), (24) and (27) with n = 1.0 and parameter values as Table 2.

TABLE 5.

Values of the sum of the leak-dependent and of the leak-independent components of ventilation for four types of storage (t_d = 5 mins, 500 - 250 Pa, full structure).

	$(k_{dep})_{max}$ (d^{-1})		$(k_{dep})_{max}$ with 60% CO_2 in enclosure (d^{-1})		$(k_{indep})_{max}$ (d^{-1})
	$n = 0.8$	$n = 1.0$	$n = 0.8$	$n = 1.0$	
Case 1, farm bin	0.05	0.03	0.06	0.04	0.08
Case 2, bag stack	0.07	0.04	0.08	0.05	0.05
Case 3, silo bin	0.14	0.11	0.21	0.15	0.03
Case 4, shed	0.12	0.09	0.17	0.11	0.10

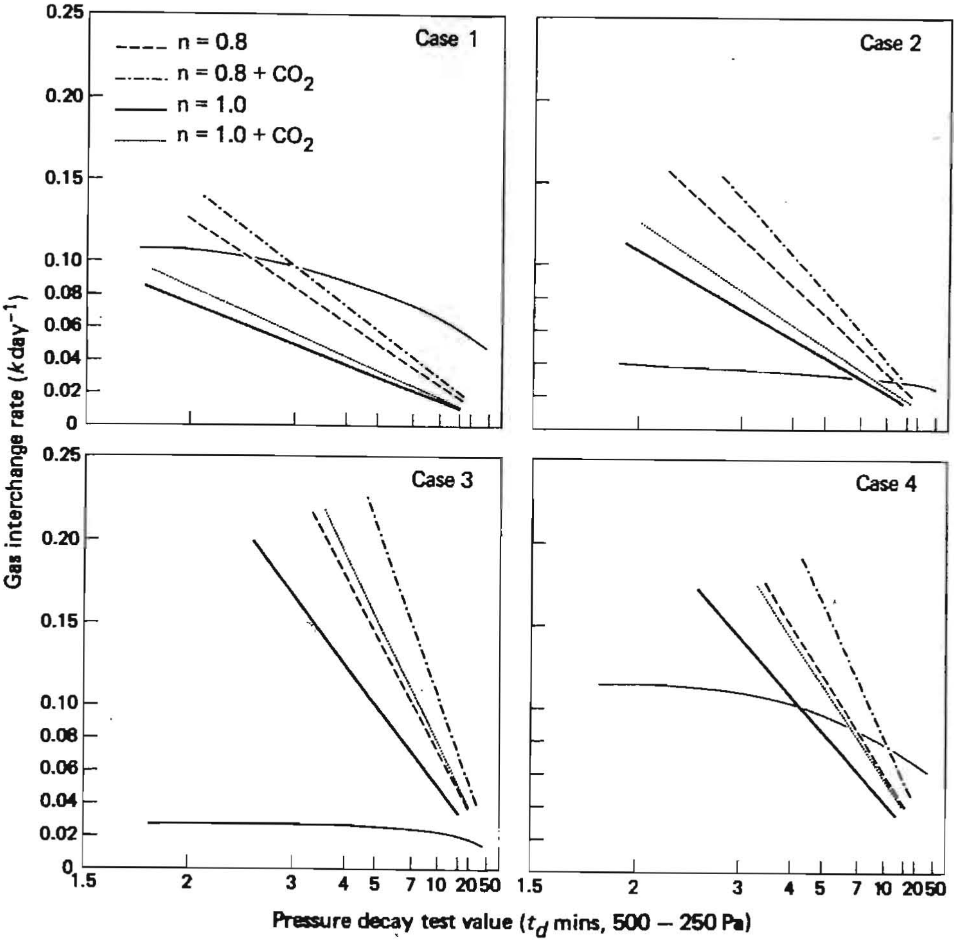

Fig. 2. Comparison of values of $(k_{dep})_{max}$ (straight lines) and $(k_{indep})_{max}$ (curved line) for four enclosures (see Table 3) showing the influence of level of sealing, as assessed by a pressure test, and the value of n and presence of 60% CO_2 in internal atmosphere.

that the 5 min decay standard is, in fact, adequate for large silo bins and that it is therefore too stringent for farm bins of the type considered here. On the basis of the model it is not possible to tell which of these two inferences is correct as the value of k_{dep} cannot be established sufficiently accurately.

(7) The specification of a particular decay time as a standard for gastightness without knowledge of the value of n, allows a substantial range of interchange rates, depending on n.

(8) The presence of 60% CO_2 substantially increases the value of $(k_{dep})_{max}$ but, since an additional 0.02 day^{-1} can be tolerated

in actual loss rate compared with that for nitrogen (Table 1), the gastightness requirements (pressure decay test time) are similar for the two techniques.

(9) While treatment failures may be caused by inadequate sealing, leading to excessive k_{dep} values, this need not always be so. Excessive values of k_{indep} can also occur.

(10) Variation in barometric pressure is unlikely to cause treatment failure except in combination with other phenomena.

(11) Short term temperature fluctuations can be a very significant cause of gas loss in some situations.

CONCLUSION

The model presented here is a useful tool for design work on storages and for investigation of some of the reasons for treatment failures and excessive gas usage in fumigations and controlled atmosphere use. It provides a framework for understanding the influence of a specific pressure decay test time on gas retention under particular circumstances. The model also exposes some of the ambiguities inherent in using simple pressure decay test times as a method of specification of gastightness.

It is hoped that this model and discussion has explained why a single pressure test standard to cover all storage structures is inappropriate. The pressure decay value, being in the order of minutes, should be set to meet the needs of particular storage types and environmental circumstances. With judgements of this kind applied well it should be possible to optimise the technology of fumigant and controlled atmosphere use. The incidence of treatment failures may then be reduced without resorting to unnecessarily high standards of sealing and unnecessary and often costly modifications to storages in misdirected attempts to reduce gas losses.

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NOTATION

A	Area (m^2)
C	Wind Pressure coefficient
D	Diffusion constant ($m^2\ s^{-1}$)
M	Molecular weight of air
N	Porosity of grain
P	Pressure (Pa, absolute)
Q	Volumetric flow rate ($m^3\ s^{-1}$)
R	Gas constant (J $kg\text{-}mol^{-1}\ K^{-1}$)
T	Temperature (K)
V	Volume (m^3)
a	Amplitude of oscillation
b	Gas flow across a leak at 1 Pa ($m^3\ s^{-1}$)
g	Acceleration due to gravity ($m\ s^{-2}$)
h	Vertical distance between leaks (m)
k	Rate constant or ventilation rate (s^{-1})
l	Length of diffusion path (m)
m	Mass of gas in enclosure (kg)
n	An empirical exponent
p	Pressure (Pa)
t	Time (s)
u	Wind velocity ($m\ s^{-1}$)
x	Distance (m)

α	Proportion of total leak represented by the smaller leak
γ	Orifice coefficient
κ	Thermal diffusivity ($m^2\ s^{-1}$)
ν	Density ($g\ m^{-3}$)
τ	Period of fluctuation (s)
ϕ	Phase angle
ω	Frequency of fluctuation (Hz)

<u>Subscripts</u>

C	Chimney effect
D	Diffusion
HS	Headspace
P	Barometric pressure
T	Temperature variation
Tb	Temperature variation in grain bulk
W	Wind
Wf	Wind fluctuations
d	Decay time
dep	Dependent on leak size
ext	External
$indep$	Independent of leak size
int	Internal
pe	Permeation
s	Surface

REFERENCES

Anon., 1972. Infiltration and Natural Ventilation, In: Handbook of Fundamentals. Am. Soc. Heat. Refrig and Aircond. Eng. Chapter 19: pp. 333-346.

Babbitt, J.D., 1945. The thermal properties of wheat in bulk. Can. J. Res. 23F: 388-401.

Barker, P.S., 1974. A theoretical consideration of the behaviour of air-fumigant mixtures in stored grains in relation to the laws of gases. Manitoba Entomol. 8: 80-84.

Banks, H.J. and Annis, P.C., 1977. Suggested procedures for controlled atmosphere storage of dry grain. CSIRO Div. Entomol. Tech. Pap. No. 13. 23pp.

Banks, H.J., Annis, P.C., Henning, R.C. and Wilson, A.D., 1980. Experimental and commercial modified atmosphere treatments of store grain in Australia. In: 'Controlled Atmosphere Storage of Grains'. (ed. J. Shejbal). Elsevier, Amsterdam, pp. 207-224.

Banks, H.J., Longstaff, R.A., Raupach, M.R. and Finnigan, J.J., 1983. Wind-induced pressure distribution on a large grain storage shed: prediction of wind-driven ventilation rates. J. stored Prod. Res. 19: 181-188

Banks, H.J., Sharp, A.K. and Irving, A.R., 1975. Gas interchange in freight containers. Proc. 1st Internat. Wking Conf. on Stored Prod. Entomol. Savannah, 1974, pp. 513-531.

Blomsterberg, A.K. and Harrje, D.T., 1979. Approaches to evaluation of air infiltration energy losses in buildings. ASHRAE Trans. 85: 797-815.

Bond, E.J., Sellen, R.A. and Dumas, T., 1977. Control of insects with phosphine in open-ended bin spouts. J. econ. Ent. 70: 22-25.

Cockroft, J.P. and Robertson, P., 1976. Ventilation of an enclosure through a single opening. Build. Environ. 11: 29-35.

de Gids, W.F., 1977. Calculation Method for the Natural Ventilation of Buildings. TNO Research Institute for Environmental Hygiene, Delft, publication No. 632, pp. 29-42.

Hill, J.E. and Kusuda, T., 1975. Dynamic characteristics of air infiltration. ASHRAE Trans. 81: 168-185.

Kreith, F. and Eisenstadt, R., 1957. Pressure drop and flow characteristics of short capillary tubes at low Reynolds numbers. Am. Soc. mech. Eng. Trans. 79: 1070-1078

Lagus, P.L., 1977. Characterisation of building infiltration by the tracer-dilution method. Energy, 2: 461-464.

Lewallen, M.J. and Brown, R.H., 1967. Oxygen-permeability of concrete silo wall sections. Trans. ASAE. 10: 114-115, 122.

Macriss, R.A., Cole, J.T., Zawacki. T.S. and Elkins, R.H., 1979. An air infiltration model for modern single family dwellings. Proc. Annual Mtg Air Pollution Control Assoc. 72. Paper 79-14.5 23 pp.

Malinowski, H.K., 1971. Wind effect on the air movement inside buildings. Proc. Symp. Wind Effects on Buildings and Structures. Tokyo. pp. 125-134.

Meiering, A.G., 1982. Oxygen control in sealed silos. Trans. ASAE. 25: 1349-1354.

Moller, F. and Pederson, S., 1978. [Air ventilation in a gastight silo.] Ugeshr. Agron. Hortonomer Forstkandidater Licentiater. 123: 899, 901-902. (in Danish).

Mulhearn, P.J., Banks, H.J., Finnigan, J.J., and Annis, P.C., 1976. Wind forces and their influence on gas loss from grain storage structures. J. stored Prod. Res. 12: 129-142.

Newman, G., 1970. Investigation of a pressure equalising system in a sealed grain silo. Inst. Agr. Engineers. J. and Proc. 25: 158-160.

Oxley, T.A., Hyde, M.B., Ransom, W.H., Hall, D.W. and Wright, F.N., 1960. The new grain bins in Cyprus. Colonial Office, London, 14pp.

Oxley, T.A. and Howe, R.W., 1944. Factors influencing the course of an insect infestation in bulk wheat. Ann. Appl. Biol. 31: 76-80.

Peterson, J.E., 1979. Estimating air infiltration into houses. ASHRAE J. 21: 60-62.

Sharp, A.K., 1982. Measurement of gas-tightness with an automatic pressure-decay timer. Sci. Tech. Froid, 1982-1: 361-367.

Sinden, F.W., 1978. Wind, temperature and natural ventilation - theoretical considerations. Energy and Buildings. 1: 275-280.

APPENDIX. CALCULATION OF VOLUME OF GAS LOST THROUGH TEMPERATURE VARIATION IN A GRAIN BULK RESULTING FROM DIURNAL HEATING OF THE SURFACE.

Consider a semi-infinite grain mass, initially at uniform temperature, bounded by a wall at $x = 0$, where x is the distance into the mass from the wall. It can be shown (Babbitt, 1945) that, with a variation in wall temperature following

$$T_s - \overline{T} = a\cos(\omega t - \phi) \tag{38}$$

the temperature at any point in the bulk is given by

$$T - \overline{T} = a\mathrm{e}^{-\sqrt{\frac{\omega}{2\kappa}}x}\cos(\omega t - \sqrt{\frac{\omega}{2\kappa}} - \phi) \tag{39}$$

The change in gas volume, dV, in an element dx, of cross-section, A, brought about by an increase in temperature from $\overline{T}$ to T is given by (derived from Equation (17))

$$\mathrm{d}V = \frac{T - \overline{T}}{\overline{T}}\mathrm{d}x\,NA \tag{40}$$

where N is the porosity of the grain bulk. Thus

$$\mathrm{d}V = \frac{aAN}{\overline{T}}\,\mathrm{e}^{-\sqrt{\frac{\omega}{2\kappa}}x}\cos(\omega t - \sqrt{\frac{\omega}{2\kappa}} - \phi)\,\mathrm{d}x \tag{41}$$

The total volume excess, ΔV, over the bulk will be given by

$$\Delta V = \int_0^\infty \frac{aAN}{\overline{T}}\,\mathrm{e}^{-\sqrt{\frac{\omega}{2\kappa}}x}\cos(\omega t - \sqrt{\frac{\omega}{2\kappa}} - \phi)\,\mathrm{d}x \tag{42}$$

$$= \frac{aAN}{\overline{T}}\sqrt{\frac{\kappa}{\omega}}\cos(\omega t - \frac{\pi}{4}) \tag{43}$$

During one complete cycle the total volume excess will be approximately twice the maximum value of V, since the loss occurs during expansion from $\overline{T}$ to T_{max} and from T_{min} to $\overline{T}$. Substituting for ΔV in Equation (7), the ventilation rate, k, from this process is thus given by

$$k = \frac{2aNA}{\overline{T}Vt}\sqrt{\frac{\kappa}{\omega}} \tag{21}$$